Magnet Architectures and Active Radiation Shielding Study with High Temperature Superconductors

NIAC Phase 2 Symposium

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Active Shielding – A New Approach

• Recent advances in superconducting magnet technology and manufacturing have opened the door for re-evaluating active shielding solutions as an alternative to mass prohibitive passive shielding

• Main Objectives
  – Analyze new coil configurations with maturing superconductor technology
  – Develop vehicle-level concept solutions and identify engineering challenges and risks
  – Shielding performance analysis

A Foundation in Active Shielding

- Wernher von Braun, 1969
  - Mighty Magnets, Superconductivity
- J. C. Sussingham, 1999
  - Significant list of references
- L.W. Townsend, 2000
  - Active shielding summarized
- J. Hoffman, 2005
  - NIAC LTS toroid, AMS
- Battiston, 2011
  - ARSSEM, Double Helix Toroid
- Among many other studies
Radiation Environment

Common GCR species on the left graph. Note the solar effects on the lower energy particles, hence the multiple curves per species. The GCR/SPE graph below shows the energy differences. *(Physics Today, Oct. 1974)*

Graphic of Earth’s Magnetosphere
Credit: THEMIS, nasa.gov

GCR: Galactic Cosmic Radiation
SPE: Solar Proton Event
Secondary particles must be accounted for in dose evaluation

- Monte Carlo analysis includes millions of particle traces to evaluate total dose on a human sized volume within the habitat
- Graphics are a special generation meant to show, at a single proton energy, the effect of the magnet field
Passive Shields

*Note the Liquid H2, 1 g/cc is fictional

Per LaRC/R. Singleterry.
6+1 Configuration

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 Solenoids Surrounding habitat</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diameter</td>
<td>m</td>
<td>8.0</td>
</tr>
<tr>
<td>Length</td>
<td>m</td>
<td>15-20</td>
</tr>
<tr>
<td>Nominal Field</td>
<td>T</td>
<td>1.0</td>
</tr>
<tr>
<td>Nominal Current</td>
<td>kA</td>
<td>40</td>
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<tr>
<td>Stored Energy</td>
<td>MJ</td>
<td>400</td>
</tr>
<tr>
<td>Inductance</td>
<td>H</td>
<td>0.5</td>
</tr>
<tr>
<td>Magnetic Pressure</td>
<td>atm</td>
<td>~4</td>
</tr>
</tbody>
</table>

- Persistent mode operation
- Flux Pump charged
- Expandability considered
Large Fully Inflated Coil

“Radial Limiters” – Fully extended
Solenoid Coil Fully Deflated then Partially Expanded

Diameter of inner Hub: ~ 1000 mm
Spoke Length: ~ 1000 mm

Superconductor draped onto “Coil Strongback”

“Coil Strongback”
A light-weight composite structure

Superconducting “Liner”

“Radial Limiters” -- fiber bundles

By vacuum pumping, the superconducting “Liner” is sucked to the “Strongback Coil” surface, closely following its contour of the “Spokes”.

AML/R. Meinke
Analyze Field in Indicated X-Y-Plane

Field in X-Y-Plane
Shielding Coils with Habitat and Compensation Coil

- 6 shielding coils of 8 meter dia.
- 6 meter dia. Habitat
- Compensation Coil
  - Reduces magnetic field in habitat area from 2,500 Gauss to less than 20 Gauss
Rest Field with Modulated-Pitch Solenoid

Pitch length decreases towards coil ends
Similar to MRI Gradient Coils

**Diameter, pitch length and current of Compensation coil optimized:**

- Diameter of Compensation Coil: 7.20 [m]
- Length of Compensation Coil: 15.8 [m]
- Current in Compensation Coil: 10220 [A]
- Mean Field in Habitat: 10.3 [Gauss]
A Cycler Approach

• A deep space cycler is our approach for an active shield architecture
  – An active shield approach would need to be useable for multiple missions
    • Architecture cost
  – An active shield design is less complex when maintained in deep space
    • Simplify thermal management systems

• Launch, Assembly and Voyage (asteroid mission discussed here)
  – Heavy lift delivery of shielding coils to low earth orbit (LEO)
    • Deploy coil array in LEO, such as the Earth-Moon L2
  – Heavy lift delivery of compensation coil and habitat (LEO)
    • Dock with Shielding coil assembly in LEO
  – Delivery of mission support (food/water/propulsion/power)
    • Mission dependent – Need a Design Reference Mission study
    • Power deployment will enable coil charging and expansion
  – Deliver spacecraft to high earth orbit (HEO) such as the Earth-Moon L2
    • Using solar electric propulsion tug or chemical
  – Delivery of crew (Crew Module)
    • Field charging prior to and after crew arrival and dock?
  – Round trip to destination and return to HEO with CM/SM lifeboat
    • Crew Undock and return home in MPCV-like vehicle
Active Radiation Shielding
6 + 1 Expansion Coil Architecture
Propulsion Shielding Potential

- Two in-space propulsion architectures selected to envelope passive shielding potential
  - Chemical (LOX/LH2): selected for significant mass; in space storage remains an issue but it was used to evaluate the significant hydrogen content for shielding
  - Very High Power Solar Electric Propulsion (SEP): selected for minimal mass (less shielding potential).
L1 – NEA Roundtrip Chemical Mission

**Input:**
- $M_{PL} = 100\ t$, $T < 1\ year$
- $I_{sp} = 400\ sec$ (LOX+LH2)

**Output:**
- $M_{prop} = 286\ t$, $M_{L1} = 386\ t$
- $\Delta v_{total} = 5.3\ km/s$

1) Departing L1 May 27, 2029
   $M_{L1} = 386\ t$, $\Delta v_1 = 0.5\ km/s$, $M_{pr,1} = 47\ t$

2) At NEA
   $\Delta v_2 = 2.1\ km/s$, $M_{pr,2} = 140\ t$

3) From NEA
   $\Delta v_3 = 2\ km/s$, $M_{pr,3} = 80\ t$

4) At L1
   $\Delta v_4 = 0.7\ km/s$, $M_{pr,4} = 19\ t$
NEA – Chemical (365 days)

SM Prop – 4 tanks
LOX/CH4, 350 s, 1.25 km/s stored dV

Dry: 16 mT

Comp coil, 8 Tm coils (not shown): 53 mT (iteration 1)

5 mT Habitat 30 mT

Tunnel with EVA port, Dock port:
3 m dia x 10 m, 0.688 in. thick

Payload mass estimated at 100 mT for propulsion mass estimates

Interplanetary Prop Module (IPM)
2 or more tanks
LOX/H2, 400 s, 5.3 km/s

H2

286 mT O2

Payload mass estimated at 100 mT for propulsion mass estimates
### Iteration 1 (phase 1)

**No End Cap Architecture**  
Not included: habitat mass, consumables, propellant, etc.

<table>
<thead>
<tr>
<th>Z</th>
<th>Total</th>
<th>Barrel Region</th>
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<tbody>
<tr>
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<td>2</td>
<td>6.6</td>
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<tr>
<td>3-10</td>
<td>22.5</td>
<td>14.3</td>
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<td>11-20</td>
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<td>8.1</td>
<td>2.6</td>
</tr>
<tr>
<td>Total</td>
<td>70.0</td>
<td>45.1</td>
</tr>
</tbody>
</table>

Limit approximately corresponds to 15 cSv *under conservative assumptions*

**cSv/rem**

The **Barrel Region** corresponds to the acceptance covered by the magnetic shield.  
*Average values of the six water cylinder positions*
**Annual Skin, BFO and Whole Body Equivalent Doses**

for Geometry 27 (NEA-C) at Solar Minimum

**Iteration 1**

No End Cap Architecture
Not included: habitat mass, consumables, propellant, etc.

**Iteration 2**

End Cap Architecture
Includes chemical LOX/LH2, MPCV, tunnel

<table>
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<td>7.6</td>
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<td></td>
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<td>6.6</td>
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<td>12.7</td>
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<tr>
<td></td>
<td>6.9</td>
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<td>36.3</td>
<td>45.5</td>
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<tr>
<td></td>
<td>30.9</td>
<td>23.2</td>
</tr>
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</table>

*Average values of the six water cylinder positions

Limit approximately corresponds to 15 cSv under conservative assumptions
### Iteration 1

**No End Cap Architecture**

Not included: habitat mass, consumables, propellant, etc.

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<td>21-28</td>
<td>8.1</td>
<td>2.6</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>70.0</strong></td>
<td><strong>36.3</strong></td>
</tr>
</tbody>
</table>

Fraction of total dose: 0.65, 0.69, 0.64

### Iteration 2

**End Cap Architecture**

Includes chemical LOX/LH2, MPCV, tunnel

<table>
<thead>
<tr>
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<tr>
<td>3-10</td>
<td>21.0</td>
<td>14.0</td>
</tr>
<tr>
<td>11-20</td>
<td>16.3</td>
<td>8.1</td>
</tr>
<tr>
<td>21-28</td>
<td>6.9</td>
<td>2.3</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>66.3</strong></td>
<td><strong>36.3</strong></td>
</tr>
</tbody>
</table>

Fraction of total dose: 0.71, 0.73, 0.70

### Iteration 3

**In work: add habitat mass**

The **Barrel Region** corresponds to the acceptance covered by the magnetic shield.

*Average values of the six water cylinder positions

Limit approximately corresponds to 15 cSv under conservative assumptions
6+1 Expandable Solenoid Shield

1 GV (0.43 GeV) Protons

Events with ionisation loss recorded in H$_2$O cylinders.

Effet Étonnoir

3000 protons generated uniformly across the two surfaces in the xy plane used to define the acceptance.
Field computed at 5.9 M points uniformly spaced in a $40 \times 40 \times 50$ m$^3$ volume using the Biot-Savart law, with 400 current loops along the 20 m solenoid cylindre, and 180 current elements in each loop.
Model & HZETRN

- An analytical-HZETRN model was developed to allow the rapid analysis of a broad range of trade space variables for a solenoid shaped, active magnetic shield design.

- This model assumes a single solenoid around the spacecraft for simplicity and provides a shielding performance analysis (mass and dose equivalent) of the 6-around-1 coil design.
  - Mass assumes commercial off the shelf materials.

HZETRN = High Charge and Energy Transport
## Summary of Key Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>8 T m</th>
<th>20 T m</th>
<th>20 T m</th>
<th>25 T m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flux Density</td>
<td>1.0 T</td>
<td>2.5 T</td>
<td>1.0 T</td>
<td>1.5 T</td>
</tr>
<tr>
<td>Diameter</td>
<td>8.0 m</td>
<td>8.0 m</td>
<td>20 m</td>
<td>16.7 m</td>
</tr>
<tr>
<td>Length</td>
<td>20 m</td>
<td>20 m</td>
<td>30 m</td>
<td>25 m</td>
</tr>
<tr>
<td>Volume</td>
<td>1,053 m³</td>
<td>1,053 m³</td>
<td>9,425 m³</td>
<td>5,475 m³</td>
</tr>
<tr>
<td>Current</td>
<td>43.5 kA</td>
<td>108.8 kA</td>
<td>50.0 kA</td>
<td>50 kA</td>
</tr>
<tr>
<td>Stored Energy</td>
<td>410 M Joule</td>
<td>2,520 M Joule</td>
<td>4580 M Joule</td>
<td>2670 M Joule</td>
</tr>
<tr>
<td>Inductance</td>
<td>0.43 Henry</td>
<td>1.1 Henry</td>
<td>3.7 Henry</td>
<td>2.1 Henry</td>
</tr>
<tr>
<td>Number of Turns</td>
<td>400</td>
<td>400/1000*)</td>
<td>600</td>
<td>500</td>
</tr>
<tr>
<td>Magnetic Pressure**)</td>
<td>4 atm</td>
<td>25 atm</td>
<td>4 atm</td>
<td>9 atm</td>
</tr>
</tbody>
</table>

*) Depending on Conductor Performance
***) \( P_m = \frac{B^2}{2\mu_o} \)
Loads and Structural Response
Forces Acting on Shielding Coil

Coils behave like 6 permanent magnets with strong repulsive forces

Inter-coil support structure needed

Forces act on conductors that are bonded to flexible fabric liner

Forces not uniform over length of solenoids

Possible bending on strong back

Distortion of ‘ideal’ cylinder geometry of each individual coil
Baseline Structural Design:

- Primary differentiation between single and multi coil simulations are: mesh density, loads definition and coil connectivity structure (Yoke)
Bolstering: Flexible Laminate Reinforcement

- Bolstering based on strain mapping (sail boat sails analogy)

Membrane Loads and Deformations (Strain mapping)

Bolster Design and Fabrication (targeted fiber tow reinforcement)
Axial Forces on Undistorted Array Solenoid
Azimuthal Forces
on Undistorted Array Solenoid
Radial Forces on Undistorted Array Solenoid

Force in Radial Direction [N/cm]
Induced Deformation in Shielding Array

Displacement field - Iteration 1

Y-Axis [mm]  X-Axis [mm]

Z-Axis [mm]

Displacement [mm]

33
Structural Modeling: Coil Alone – Rigid Laminate

• Models 1 & 2 (model 2 shown):
  – von Mises Stress Comparison: Maximum Model 2 stress is 39.9% less than Model 1. Highest stress in fillet, far from imposed loads @ spline tip. Compliant structure spreads load.

Model 2 vs. Model 1: lighter, not as stiff and maximum operational $\sigma$ may be lower. How does added displacement affect the field?

Displacement scale: 4x
Summary: Weight Performance As Analyzed

Performance relative to current technology readiness level (TRL) 6-7
- Rigid and flexible composite structures perform well with regards to strength requirements
- Estimated mass

• **Cylinder – 7,448 lbm**
  - **Fiber Material:** TorayCA T1000G
  - **Construction:** 2 plies @ ±45° orientation
    - Cylinder: ¼” diameter tows
    - Limiter: 0.354” diameter tows
    - Local Bolster: ½” diameter tows
  - **Matrix:** HexPly 954-6 cyanate epoxy resin.
  - **Film:** DuPont Kapton E.

• **Strongback – 78,415 lbm**
  - **Fiber Material:** Strongback: TorayCA M55J
    - Spar and Batten: TorayCA T100G
  - **Construction:** 0°/90° orientation
    - Strongback: fiber, 32 plies @ Spars: fiber, 2”x1/2” tube, plies TBD
    - Battens: 1” diameter rod, plies TBD
  - **Matrix:** HexPly 954-6 cyanate epoxy resin.

• **Yoke – 2,608 lbm**

• **Total – 88,471 lbm**
Mass Summary

• **Strong-back mass needs work**
  – Current design utilizes today’s available materials and is a foundation to future iterations on design and incorporation of advanced materials

• **Minimize launch mass and assembly complexity**
  – Block 2 SLS: desire single launch of 6 coils to LEO
  – Recent analysis suggests SLS Block 2 delivery of 3 coils to LEO with current off the shelf composites

SLS = Space Launch System
Testing
Expandable Coil – Collapsed (AML)
Inserting into Helium Cryostat
YBCO Test (JSC)
Coil Expansion Test (JSC)

Arrival to Test Site

LN2 Bath Refill

Thermal Settling

Post Test Condensation

Test Complete
Quench Highlights
Stored Energy

6+1 coil array system to protect the crew from solar and galactic radiation.

- Volume per Coil: ~ 1000 m³
- Nominal Current: ~ 40 kA
- Stored Energy: ~ 400 MJ
- Inductance: ~ 0.4 H

Stored Energy sufficient to melt 570 kg Cu starting at 50 K
Quench -- Operational Issue of Superconductors

What causes a Quench?

Figure 1: Disturbance energy spectrum acting in superconducting devices presented as energy density in mJ/cm² versus time duration of the acting disturbance. Stability and Protection of SC Magnets – A Discussion”, Y. Iwasa, IEEE Transactions on Applied Superconductivity, p. 1615, June 2005.
Quenching of Superconducting Coils
Quench Protection
HTS Quench Protection Issues

![Graph showing cost or difficulty vs. $T_{op}$ [K]]

- Protection Conductor
- Stability Cryogenics
- Mechanical

LTS  HTS

(? Iwasa 05/08/03)
Summary

• Quench protection of large LTS magnets standard technique using passive and active methods
• Active quench protection requires reliable quench detection which constitutes potential risk itself
• Quench detection in HTS conductors is unsolved due to extremely low quench propagation velocity
• Conductor margin for mission critical shielding coils needs to be very large (e.g., MRI coils never quench)
• Expandable shielding coils require high heat conductivity of coil support fabric.
• Graphene-like material might be required

We don’t have a solution yet → NIAC
Acknowledgements:

A lot of the presented information on quench has been borrowed from publications of the following people:

- P. Ferracin
- Y. Iwasa
- C.E. Oberly
- S. Prestmon
- J. Schwartz
Phase 2 Goals (Remaining)

• The remaining tasks, as planned, include:
  – Failure Scenarios / Quench Protection
  – Shielding Optimization
  – Continued Dose Reduction Performance Analysis (Fringe Field, Habitat mass, GEANT4)
  – Finalize Technology Roadmap, Cost Analysis
  – Coil Expansion Test
  – Final Reporting
Considerations

• How to better manage end cap dose?
  – Fringe field MC analysis
  – Multiple LH2 propellant tanks instead of 1 tank?
  – Expandable habitat benefit?
  – Can solar arrays play a part in thermal management?
  – Can shielding coils be used as energy storage?
Active Radiation Shielding
6 + 1 Expansion Coil Architecture

Questions?
Backup
Environments

• Publications on static magnetic field environments and its bio-effects were reviewed. Short-term exposure information is available suggesting long term exposure may be okay. Further research likely needed.

• Magnetic field safety requirements exist for controlled work environments. The following effects have been noted with little noted adverse effects
  – Magnetohydrodynamic (MHD) effects on ionized fluids (e.g. blood) creating an aortic voltage change
  – MHD interaction elevates blood pressure (BP)
    • 5 Tesla equates to 5% BP elevation
  – Prosthetic devises and pacemakers are an issue (access limit of 5 gauss).
    • Earth field ~0.5 gauss

Ref.:
Thermal System

• Requires flexible low pressure helium gas circulation loop development for an expandable coil system
• A solar shield was considered in lieu of the helium vapor cooling system however, such a solar shield would not get the coils down to the desired temperature of 40 – 60K
• Power required
  – Cryocoolers will need 600 W at COP 32 W/W and 1.25 contingency for a total of 24kW
    • includes 380 W for compensation coil
    • Cools to 40 K, coolant loop picks up 10W with a 2 K temperature rise in the circuit for a pressure drop of ~200 Pa.

*COP – Coefficient of Performance

Florida State University/S. Van Sciver, Ph.D
State of the Art High Temperature Superconductor (HTS)

- **Low Temperature Superconducting**
  - Typical Operation: <5K - Boiling point of liquid Helium
  - Most prevalent use is with MRI medical machines

- **High Temperature Superconducting**
  - Typical Operation: ≤ 77K - Boiling point of liquid Nitrogen
  - HTS, such as YBCO, is not sensitive to conductor movement such as the supersensitive LTS
  - HTS can operate in deep space environment
  - A tape conductor is needed for solenoid coils such as the magnet systems presented here.